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(54) **SYSTEM AND METHOD FOR DETERMINING HARMONIC CONTRIBUTIONS FROM NON-LINEAR LOADS WITHOUT DISCONNECTING ANY LOAD**

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**Related U.S. Application Data**

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(60) Provisional application No. 60/503,003, filed on Sep. 15, 2003.

(51) **Int. Cl.**
***G01R 21/00*** (2006.01)
*G06F 13/00* (2006.01)

(52) **U.S. Cl.** ........................ **702/60**; 702/181; 702/182; 702/188

(58) **Field of Classification Search** ............. 702/57–62, 702/64, 65, 124, 126, 187, 188, 189; 700/44; 340/657, 658; 324/623; 706/39
See application file for complete search history.

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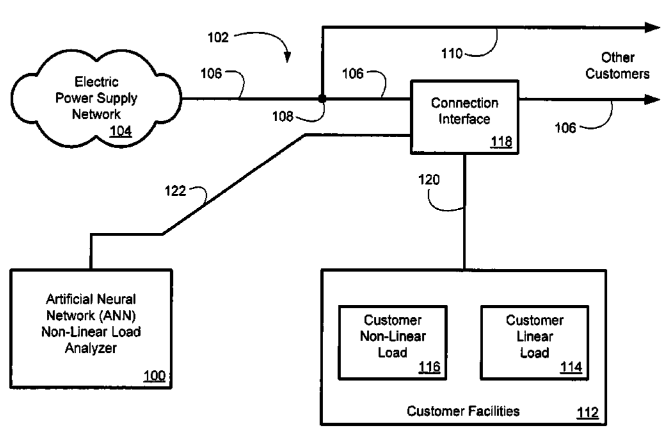
(57) **ABSTRACT**

A system and method for determining non-linear load harmonics impact on the voltage distortion at the point of common coupling is disclosed. Briefly described, one embodiment is a method comprising metering voltage on an electric power system; metering current on the electric power system; determining a predicted voltage based upon the metered current; comparing the predicted voltage with the metered voltage; and determining a harmonic voltage component using a plurality of weights determined when the predicted voltage converges with the metered voltage.

**21 Claims, 10 Drawing Sheets**



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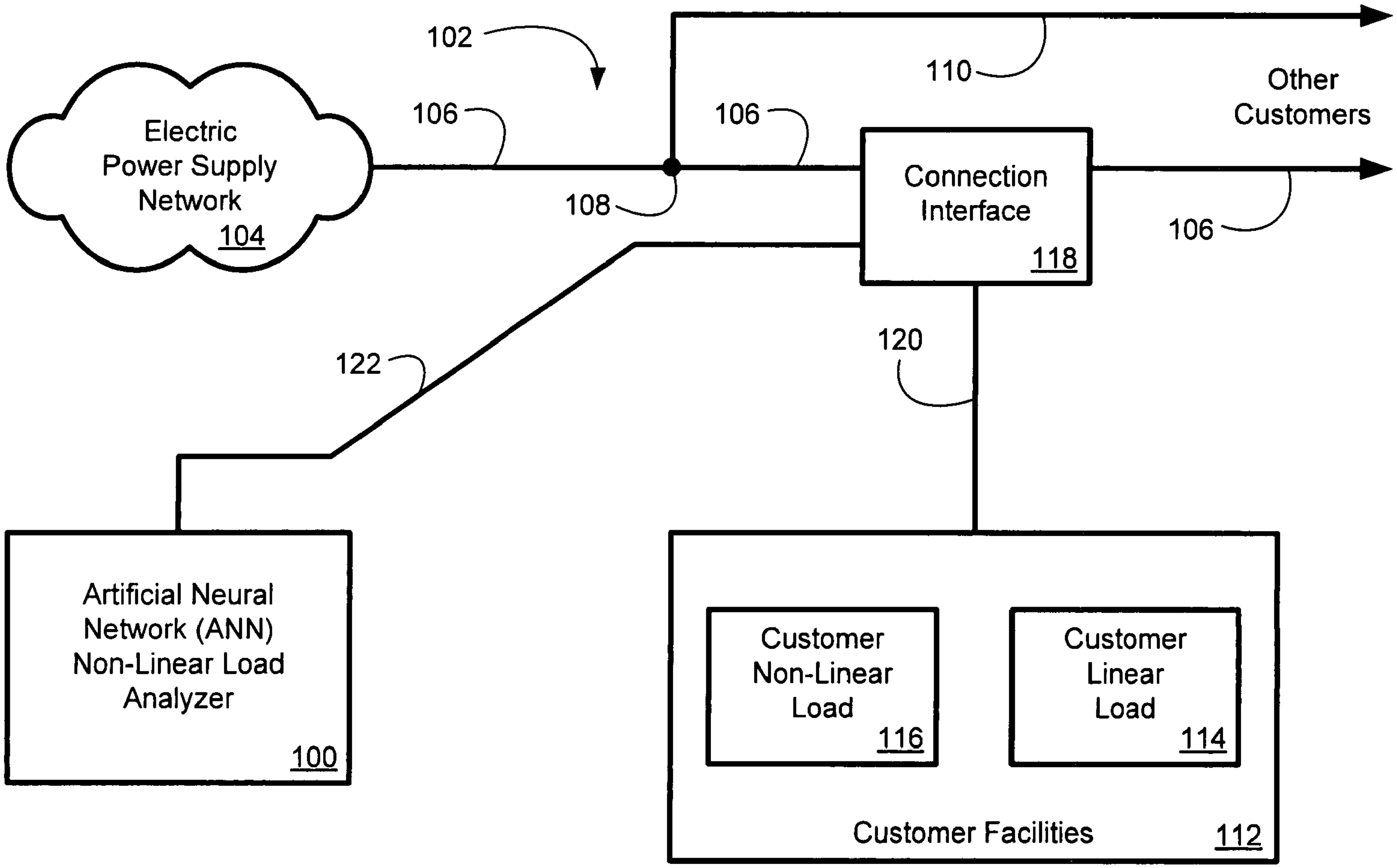
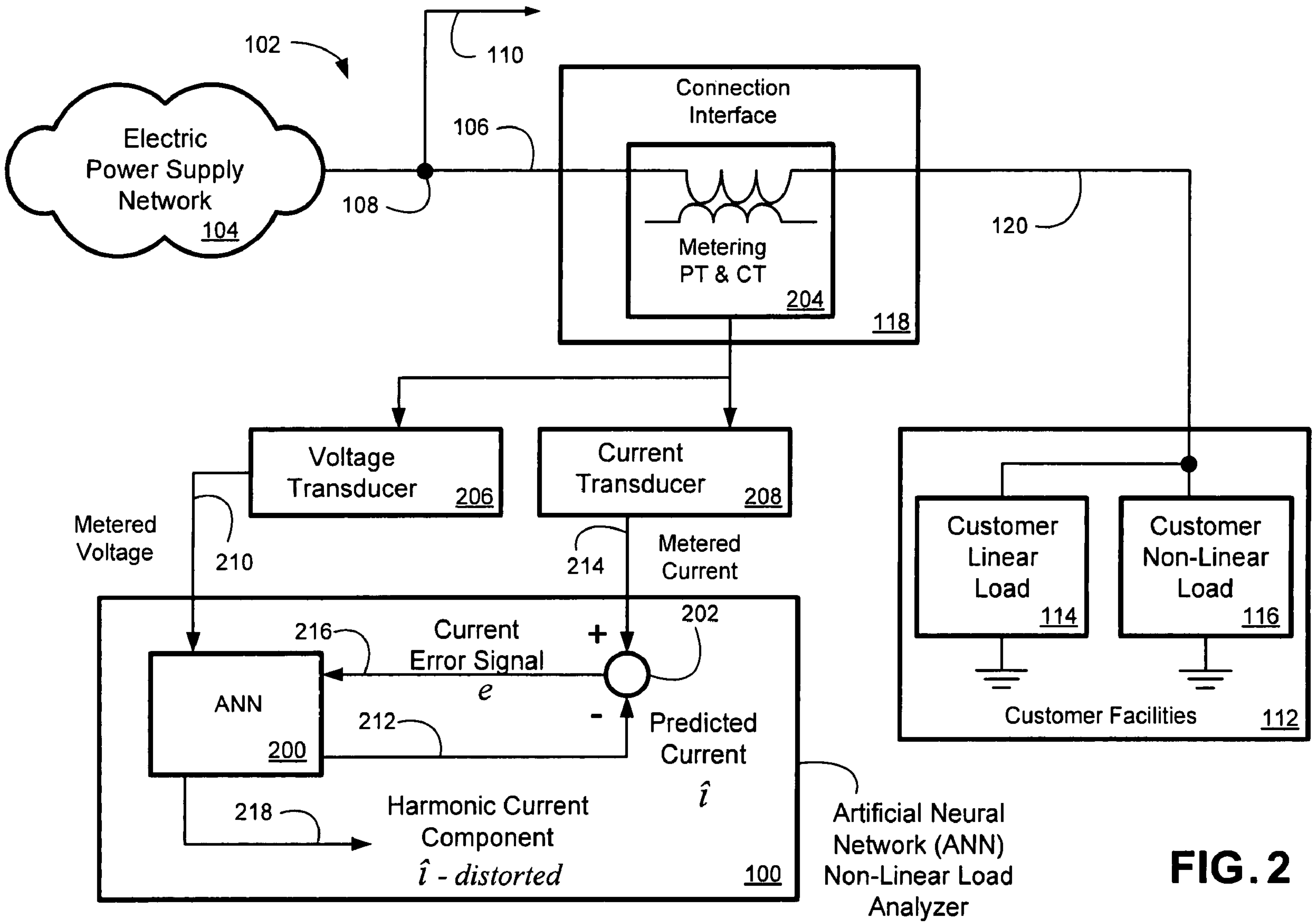

102
Electric Power Supply Network
104
106
106
108
110
Other Customers
Connection Interface
118
106
120
122
Artificial Neural Network (ANN) Non-Linear Load Analyzer
100
Customer Non-Linear Load
116
Customer Linear Load
114
Customer Facilities
112

FIG. 1



102
110
106
108
Electric Power Supply Network 104
Connection Interface
Metering PT & CT 204
118
120
Voltage Transducer 206
Current Transducer 208
Metered Voltage
210
214
Metered Current
202
+
-
216
Current Error Signal
e
ANN 200
212
Predicted Current
î
218
Harmonic Current Component
î - distorted
100
Artificial Neural Network (ANN) Non-Linear Load Analyzer
Customer Linear Load 114
Customer Non-Linear Load 116
Customer Facilities 112


FIG. 2

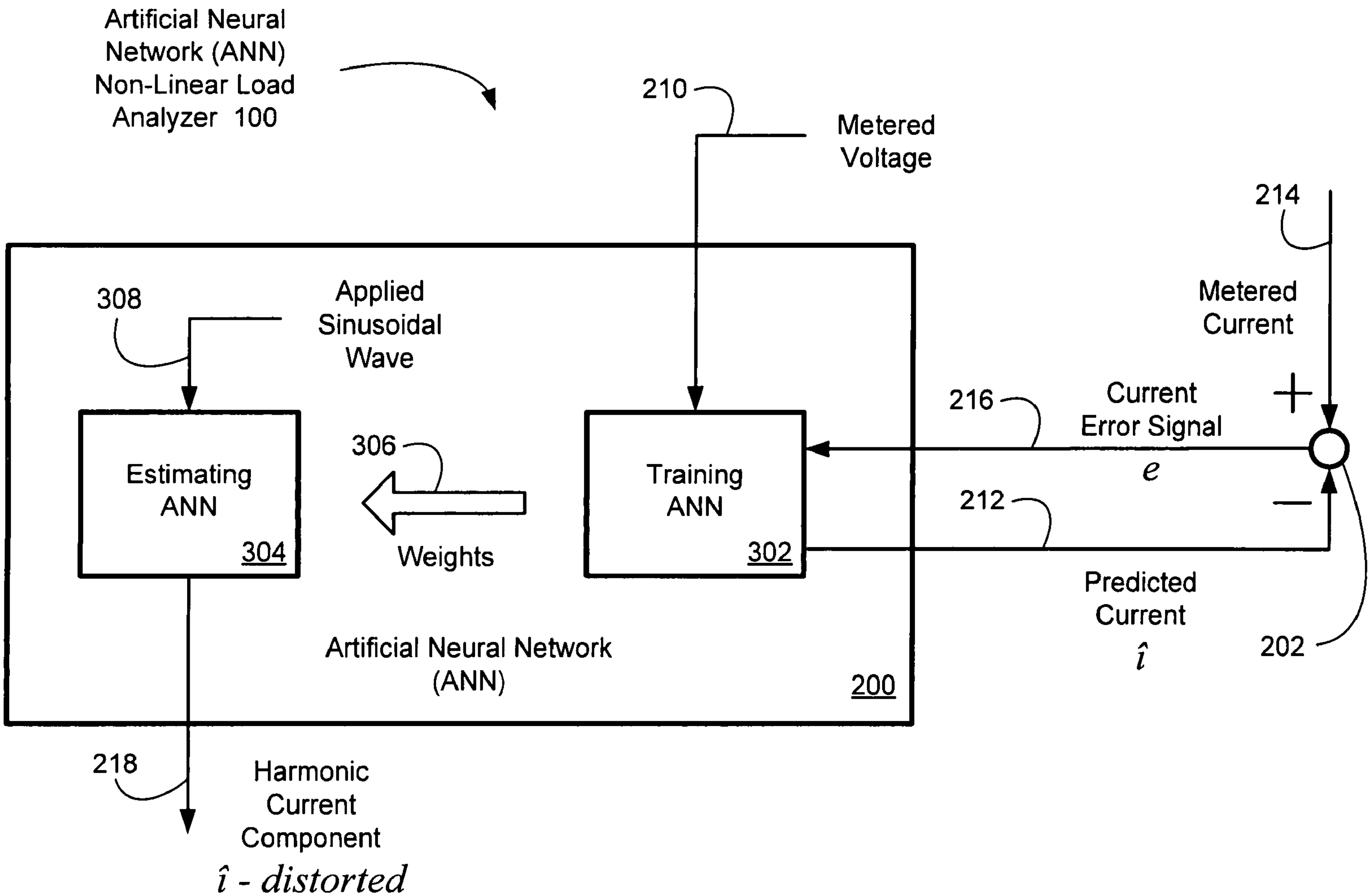
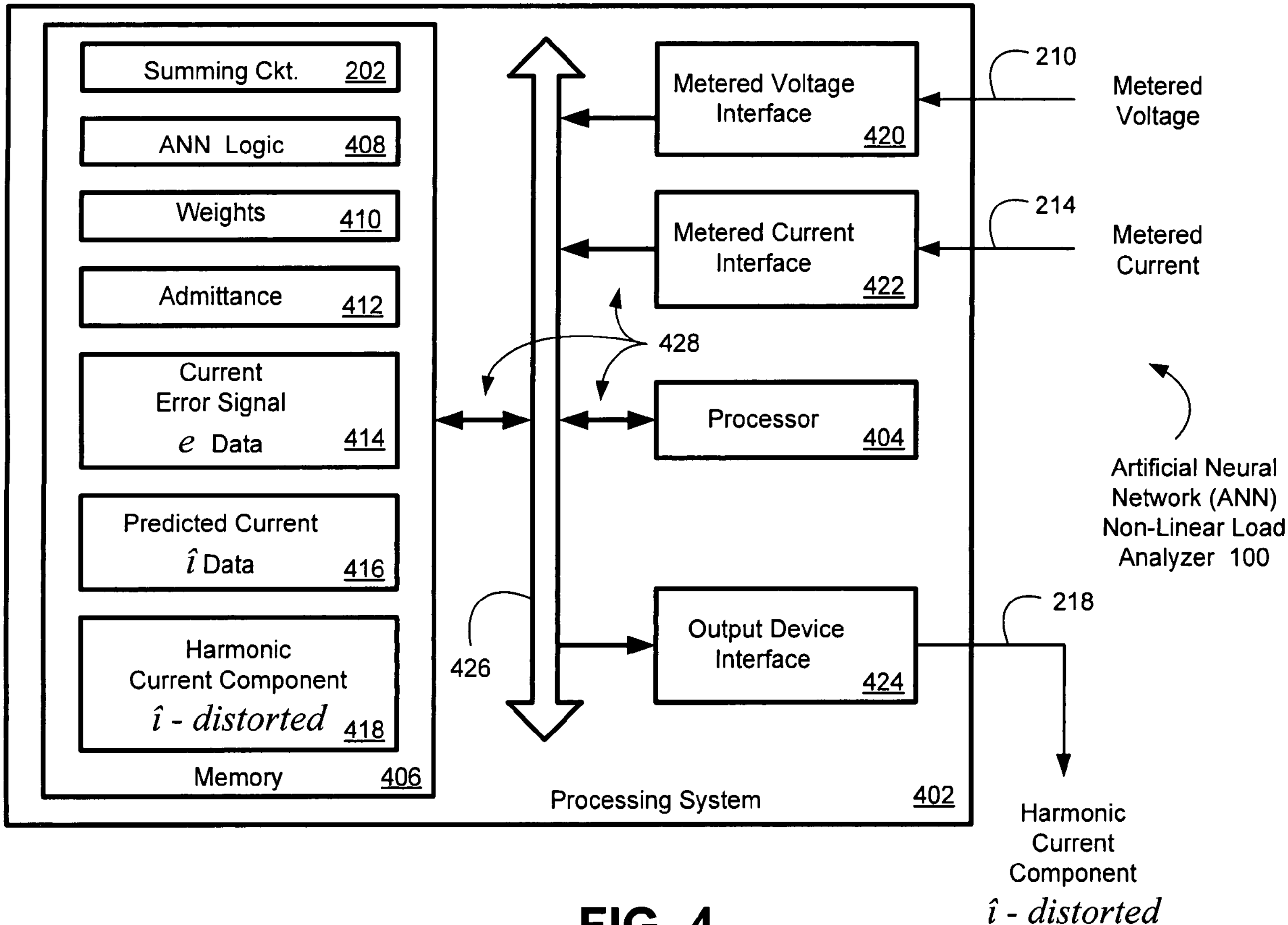

Artificial Neural Network (ANN) Non-Linear Load Analyzer 100
210
Metered Voltage
214
Metered Current
308
Applied Sinusoidal Wave
Estimating ANN
304
306
Weights
Training ANN
302
216
Current Error Signal
e
+
212
−
Predicted Current
î
202
Artificial Neural Network (ANN)
200
218
Harmonic Current Component
î - distorted

FIG. 3



Summing Ckt. 202
ANN Logic 408
Weights 410
Admittance 412
Current Error Signal $e$ Data 414
Predicted Current $\hat{i}$ Data 416
Harmonic Current Component $\hat{i}$ - *distorted* 418
Memory 406
426
428
Metered Voltage Interface 420
Metered Current Interface 422
Processor 404
Output Device Interface 424
Processing System 402
210
Metered Voltage
214
Metered Current
Artificial Neural Network (ANN) Non-Linear Load Analyzer 100
218
Harmonic Current Component $\hat{i}$ - *distorted*


FIG. 4

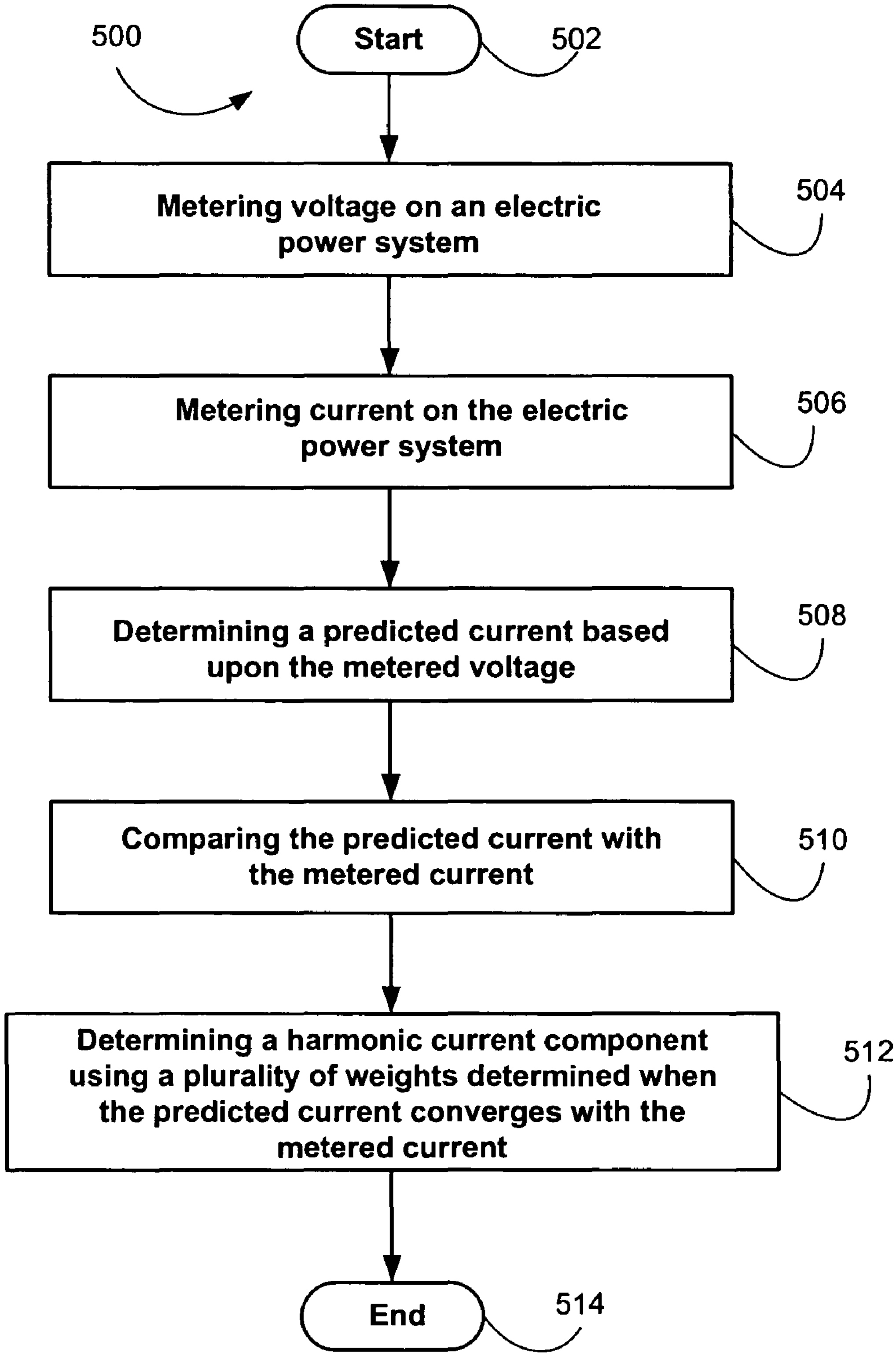

500
Start
502
Metering voltage on an electric power system
504
Metering current on the electric power system
506
Determining a predicted current based upon the metered voltage
508
Comparing the predicted current with the metered current
510
Determining a harmonic current component using a plurality of weights determined when the predicted current converges with the metered current
512
End
514

FIG. 5

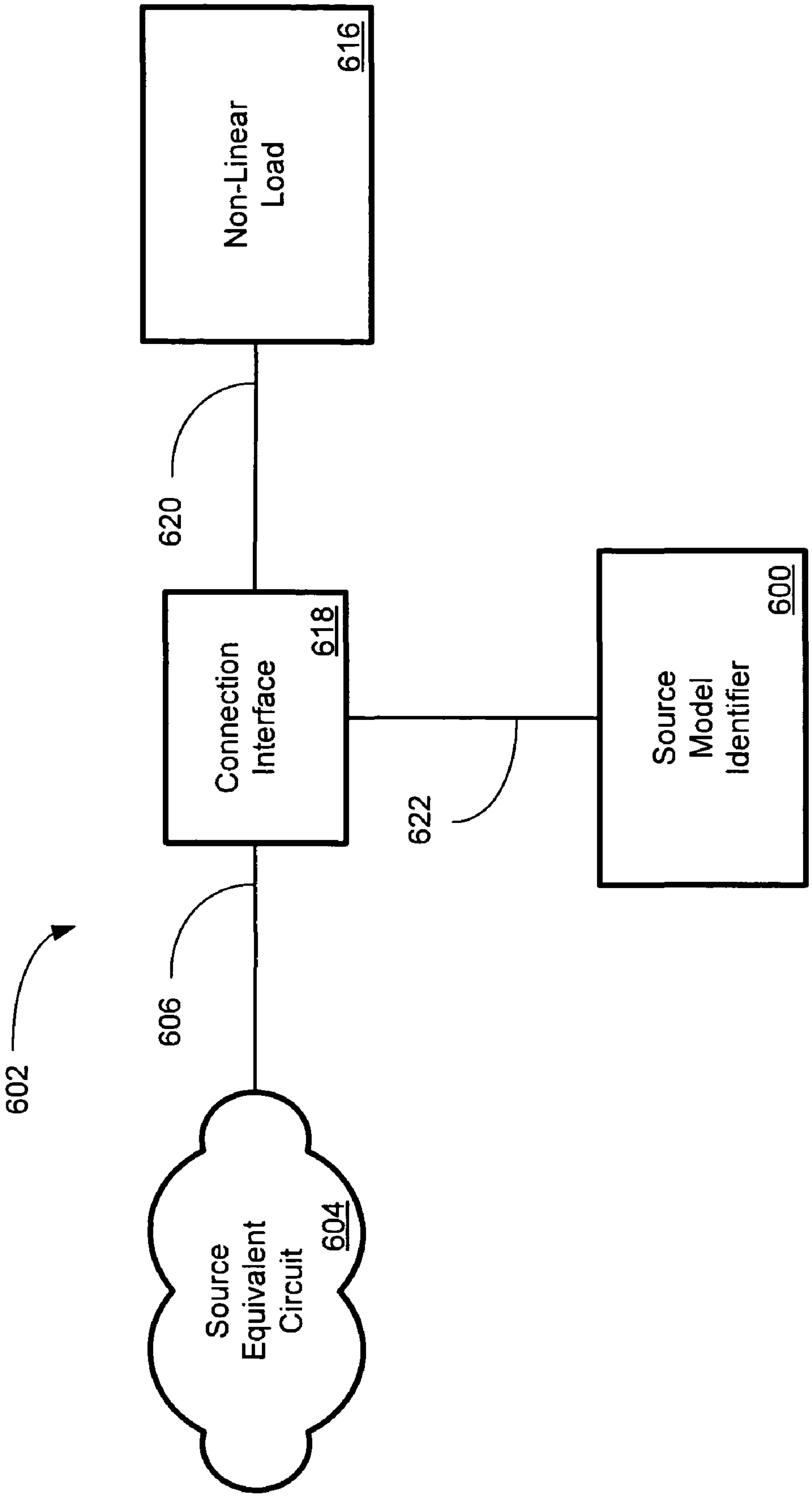

Non-Linear Load
616
620
Connection Interface
618
622
Source Model Identifier
600
602
606
Source Equivalent Circuit
604

FIG. 6

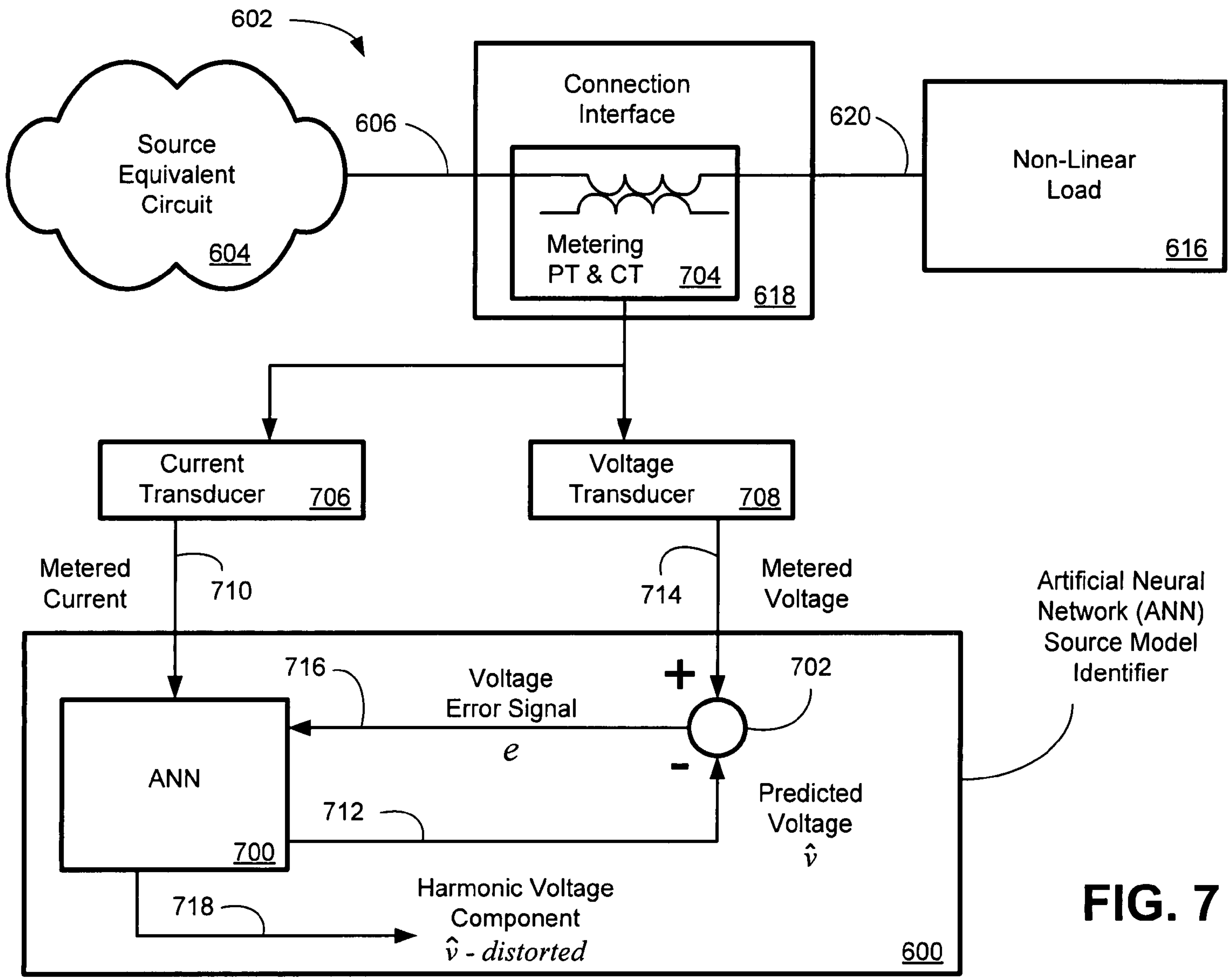

602
Source Equivalent Circuit
604
606
Connection Interface
Metering PT & CT
704
618
620
Non-Linear Load
616
Current Transducer
706
Voltage Transducer
708
Metered Current
710
714
Metered Voltage
Artificial Neural Network (ANN) Source Model Identifier
716
Voltage Error Signal
e
+
-
702
ANN
700
712
Predicted Voltage
$\hat{v}$
718
Harmonic Voltage Component
$\hat{v}$ - distorted
600

FIG. 7

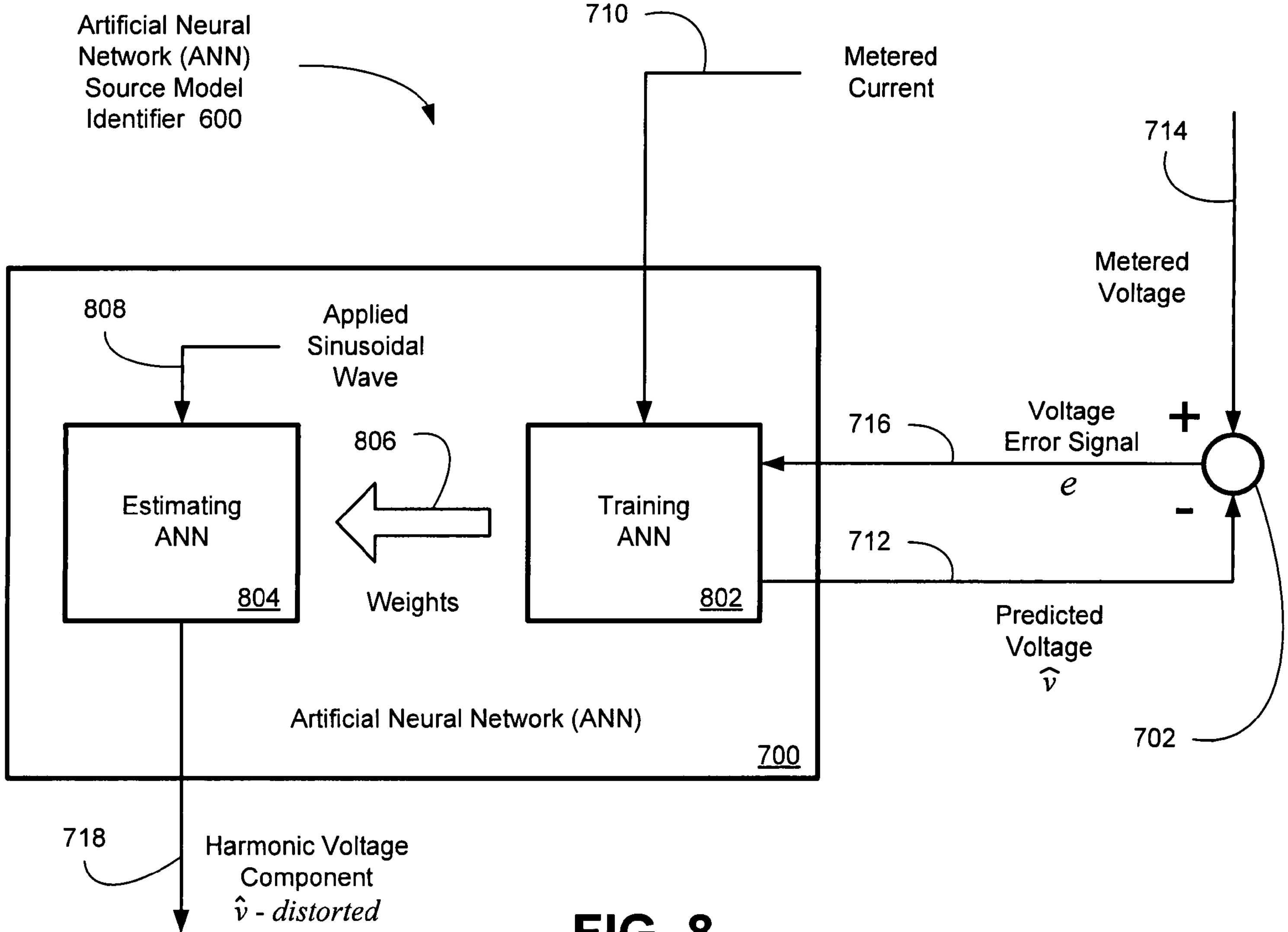

Artificial Neural Network (ANN) Source Model Identifier 600
710
Metered Current
714
Metered Voltage
808
Applied Sinusoidal Wave
Estimating ANN
804
806
Weights
Training ANN
802
716
Voltage Error Signal
e
+
-
712
Predicted Voltage
$\hat{v}$
702
Artificial Neural Network (ANN)
700
718
Harmonic Voltage Component
$\hat{v}$ - distorted

FIG. 8

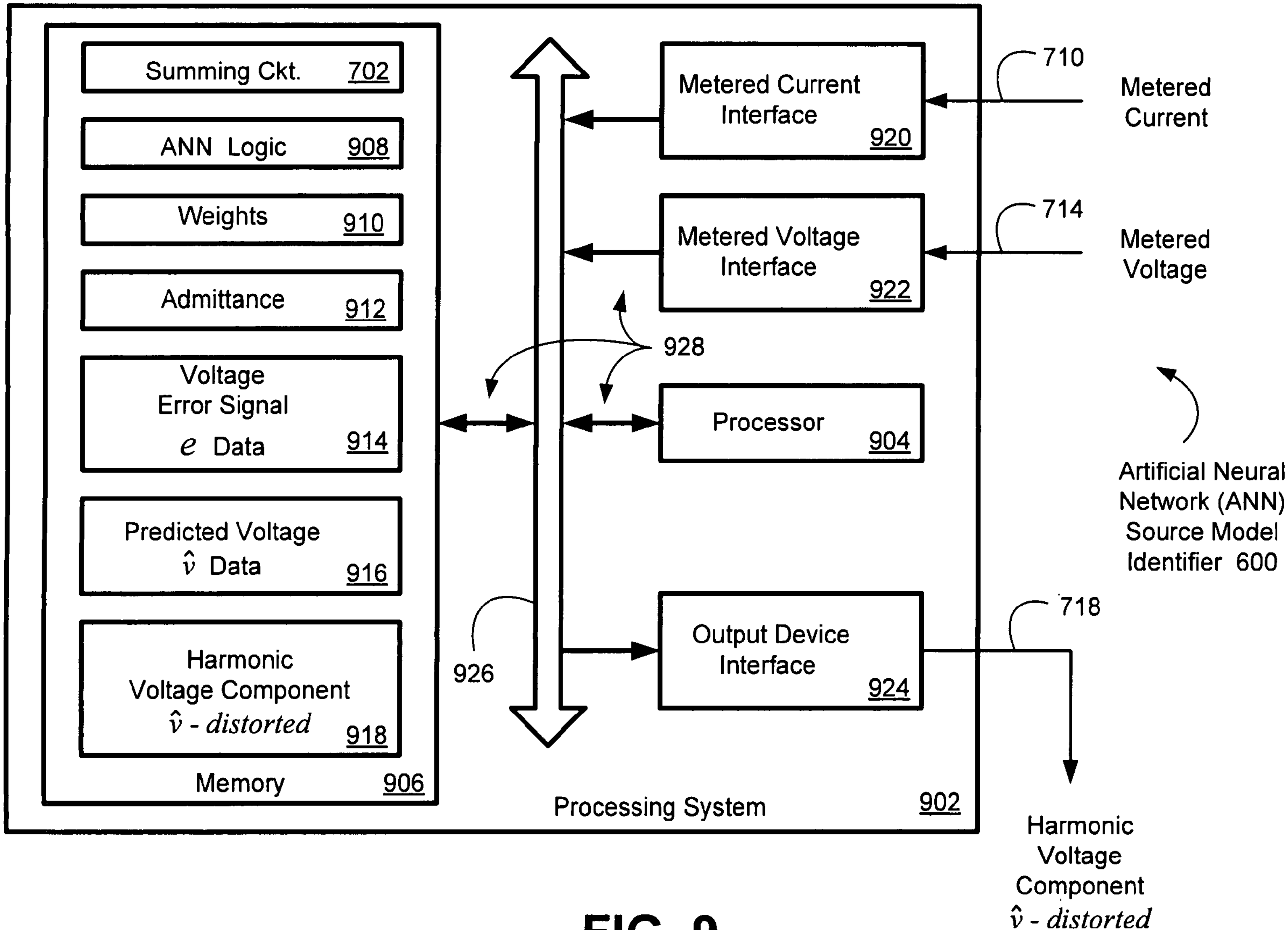

Summing Ckt. 702
ANN Logic 908
Weights 910
Admittance 912
Voltage Error Signal $e$ Data 914
Predicted Voltage $\hat{v}$ Data 916
Harmonic Voltage Component $\hat{v}$ - *distorted* 918
Memory 906
Metered Current Interface 920
Metered Voltage Interface 922
Processor 904
Output Device Interface 924
926
928
Processing System 902
710
Metered Current
714
Metered Voltage
Artificial Neural Network (ANN) Source Model Identifier 600
718
Harmonic Voltage Component $\hat{v}$ - *distorted*

FIG. 9

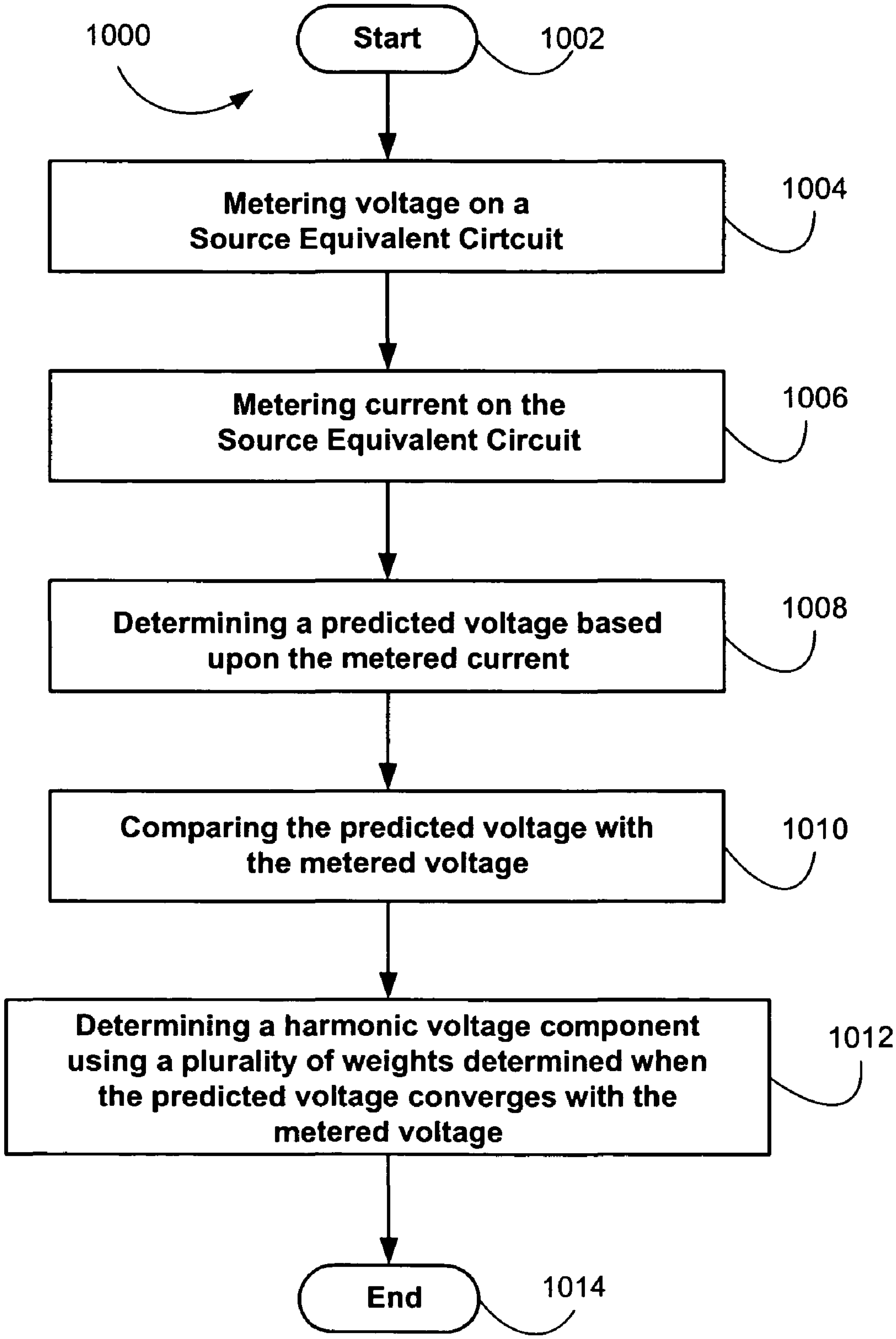

1000
Start
1002
Metering voltage on a
Source Equivalent Cirtcuit
1004
Metering current on the
Source Equivalent Circuit
1006
Determining a predicted voltage based
upon the metered current
1008
Comparing the predicted voltage with
the metered voltage
1010
Determining a harmonic voltage component
using a plurality of weights determined when
the predicted voltage converges with the
metered voltage
1012
End
1014

FIG. 10

# SYSTEM AND METHOD FOR DETERMINING HARMONIC CONTRIBUTIONS FROM NON-LINEAR LOADS WITHOUT DISCONNECTING ANY LOAD

## CROSS REFERENCE TO RELATED APPLICATION

This application is a continuation-in-pad of U.S. utility application entitled "System and Method for Determining Harmonic Contributions from Non-Linear Load," assigned Ser. No. 10/940,101, filed Sep. 14, 2004, now issued as U.S. Pat. No. 7,013,227, which claimed the benefit of U.S. provisional application entitled, "Method to Discriminate Between the Contributions of the Customer and the Power System to the Harmonic Disturbance," assigned Ser. No. 60/503,003, filed Sep. 15, 2003, both of which are entirely incorporated herein by reference.

## TECHNICAL FIELD

Various embodiments are generally related to electric power supply systems and, more particularly, are related to systems and methods for identifying power system harmonics using an artificial neural network.

## BACKGROUND

In electrical power supply networks, harmonics is a term used to describe the shape or characteristic of a distorted non-sinusoidal voltage or current waveform with respect to the fundamental frequency sine wave. Harmonic currents generated by non-linear loads, such as power electronic equipment, arc furnaces, saturating inductances, and other types of solid-state load devices, are injected into an electric power supply network. Such injected harmonic currents distort the supply source in an undesirable manner. These harmonic currents are sometimes referred to as contributions from the customer.

Harmonic currents cause harmonic voltage drops when harmonic currents generated by the customer's non-linear loads are injected into the electric power supply network. Accordingly, the supply voltage at the customer is no longer sinusoidal. Harmonic currents that distort the sinusoidal supply voltage (and/or supply current) in an electric power supply network give rise to several problems, such as: creating distorted supply voltages to loads, which in some cases cause overheating of customer equipment, or additional losses and overheating of network equipment, creating additional losses in transformers and/or cables, inducing electromagnetic interference onto neighboring telecommunication circuits, creating light flicker, causing malfunctioning of metering, current and/or voltage transducers, and/or causing malfunctioning of protection systems.

The resultant distorted load current, when measured or metered at the connection point of the customer to the electric power supply network, consists of two components; that due to contributions from the customer's non-linear load, and that due to contributions from the power system. Accordingly, it is desirable to distinguish between these two components, particularly without disconnecting the customer from the network to perform conventional load testing or analysis.

Other customers may be connected to the same connection point, or relatively close to the connection point, of the customer having loads that generate undesirable harmonic currents. Since these harmonic currents are injected into the electric power supply network, the supply voltage (and/or current) provided to the other customers may be distorted by the customer having the non-linear loads (that do cause harmonics). Accordingly, these other customers may not receive an acceptable level of power quality from the electric power supply network, thereby degrading performance of their load devices.

These other customers may have linear loads (that do not cause harmonics) and/or non-linear loads (that do cause harmonics). In some situations, the non-linear loads of the other customer, by themselves, would not otherwise cause significant unacceptable distortions in the supply voltage. However, the distortions from both customers may have a cumulative effect on the total harmonic distortion in the supply voltage. Accordingly, it is desirable to distinguish between harmonic distortion contributions from a plurality of customers supplied from the electric power supply network.

Furthermore, traditional testing methods provide results that are problematic at best. That is, since the non-linear loads may be on or off at the time of testing, it is problematic whether or not testing results accurately reflect harmonics of interest. For example, if the test is conducted during the day, harmonics induced by solid-state lighting ballasts may or may not be on at the time of testing. In a large plant, determining when a particular solid-state controlled motor is operating requires coordination. If many solid-state controlled motors are in the plant, coordination becomes even more difficult. Furthermore, even if all of the solid-state controlled motors could be simultaneously operating during the test, or if testing results of individual motors could be computationally aggregated, is the resultant harmonic contribution from all of the solid-state controlled motors a reasonable representation of actual operating conditions of the plant? Accordingly, it is desirable to be able to test for harmonic contributions on an ongoing basis, and to differentiate harmonic contributions from individual customers when multiple customers are connected at a common connection point (or relatively close together).

## SUMMARY

A system and method for determining harmonics caused by non-linear loads are disclosed. Briefly described, one embodiment is a method comprising metering voltage on an electric power system; metering current on the electric power system; determining a predicted current based upon the metered voltage; comparing the predicted current with the metered current; and determining a harmonic current component using a plurality of weights determined when the predicted current converges with the metered current.

Another embodiment is a system comprising an artificial neural network configured to receive information corresponding to metered voltage, to train itself such that a predicted current is determined which converges with a metered current, and to determine a harmonic current component using a plurality of weights determined when the predicted current converges with the metered current; and a processor configured to execute the artificial neural network.

Another embodiment is an artificial neural network that determines harmonics caused by non-linear loads, comprising a training artificial neural network that determines a predicted current from a metered voltage, and that determines a plurality of weights when the predicted current converges with a metered current; and an estimating artificial neural network that determines a harmonic current component using the determined weights received from the training artificial neural network.

Another embodiment is a method comprising metering voltage on an electric power system; metering current on the electric power system; determining a predicted voltage based upon the metered current; comparing the predicted voltage with the metered voltage; and determining a harmonic voltage component using a plurality of weights determined when the predicted voltage converges with the metered voltage.

Another embodiment is a system comprising an artificial neural network configured to receive information corresponding to metered current, to train itself such that a predicted voltage is determined which converges with a metered voltage, and to determine a harmonic voltage component using a plurality of weights determined when the predicted voltage converges with the metered voltage; and a processor configured to execute the artificial neural network.

Another embodiment is an artificial neural network that determines harmonics caused by non-linear loads, comprising a training artificial neural network that determines a predicted voltage from a metered current, and that determines a plurality of weights when the predicted voltage converges with a metered voltage; and an estimating artificial neural network that determines a harmonic voltage component using the determined weights received from the training artificial neural network.

## BRIEF DESCRIPTION OF THE DRAWINGS

The components in the drawings are not necessarily to scale relative to each other. Like reference numerals designate corresponding parts throughout the several views.

FIG. **1** is a block diagram illustrating an embodiment of the artificial neural network (ANN) non-linear load analyzer coupled to a simplified single-line diagram of an electric power supply network.

FIG. **2** is a block diagram illustrating in greater detail an embodiment of the ANN non-linear load analyzer coupled to the simplified single-line diagram of the electric power supply network.

FIG. **3** is a conceptual block diagram illustrating an embodiment of the ANN non-linear load analyzer.

FIG. **4** is a block diagram illustrating in greater detail an exemplary embodiment of an ANN non-linear load analyzer.

FIG. **5** is a flowchart illustrating an embodiment of a process for determining harmonic components using an embodiment of the ANN non-linear load analyzer.

FIG. **6** is a block diagram illustrating an embodiment of an ANN source model identifier coupled to a simplified single line diagram of a source equivalent circuit.

FIG. **7** is a block diagram illustrating in greater detail an embodiment of the ANN source model identifier coupled to the simplified single line diagram of the source equivalent circuit.

FIG. **8** is a conceptual block diagram illustrating an embodiment of the ANN source model identifier.

FIG. **9** is a block diagram illustrating in greater detail an exemplary embodiment of an ANN model source identifier.

FIG. **10** is a flow chart illustrating an embodiment of a process for determining harmonic components using an embodiment of the ANN source model identifier.

## DETAILED DESCRIPTION

The artificial neural network (ANN) non-linear load analyzer **100** provides a system and method for determining harmonic contributions from non-linear loads. FIG. **1** is a block diagram illustrating an embodiment of the ANN non-linear load analyzer **100** coupled to a simplified single-line diagram of a portion an electric power supply service system **102**. Service system **102** is ultimately coupled to, and power supplied from, the electric power supply system **104**. Service system **102** may represent either a single-phase or a three-phase system. Furthermore, the operating voltage of service system **102** may range from customer service voltage, to a distribution voltage, up through EHV (extra high voltage). Also, service system **102** may be radial or part of a network.

Typically, electric power supply network **104** provides service to customers via a conductor **106**. Often, the service provider provides service to multiple customers over a common component, illustrated here as conductor **106**. In some cases, a tap **108** on conductor **106** provides coupling to a second conductor **110**, which then extends to the other customer(s). Or, the customer facilities **112** of interest, having the linear load **114** and the non-linear load **116**, may tap off from the conductor **106** at the connection interface **118**. Here, conductor **120** is illustrated as providing service from the connection interface **118** to the customer facilities **112**.

It is appreciated that the above-described service system **102** is a very simplified diagram of an exemplary service system. Other service systems may provide service using transformers (not shown), or provide service directly from a substation bus bar (not shown). Service voltages may vary from one service system to another, or may be of the same voltage. Also, voltages along a service system may vary if transformers are employed to alter voltages. As noted above, service system **102** may represent either a single-phase and/or a three-phase system. For example, but not limited to, conductor **106** could be a three-phase conductor network and the service provided to the customer facilities **112** could be single-phase.

Many service variations are possible which may be analyzed for harmonics by embodiments of the ANN non-linear load analyzer **100**. Accordingly, the ANN non-linear load analyzer **100** may be configured to couple to single-phase, two phase and/or three-phase systems; may be configured to couple to various system voltages; and may even be configured to couple to power supply systems of different operating frequencies (such as, but not limited to, the 60 hertz system commonly employed in the United States, or the 50 hertz system commonly employed in European systems).

Embodiments of the ANN non-linear load analyzer **100** are configured to conveniently couple to a service system **102**, and/or the customer facilities **112**, such that data may be collected to determine harmonic components caused by a customer's non-linear load **116**. In FIG. **1**, a simplified connector **122** illustrates the ANN non-linear load analyzer **100** coupled to the connection interface **118** that provides service to the customer tapped off of conductor **106** in this simplified example. Greater detail of the various connection aspects of the ANN non-linear load analyzer **100** are provided below. However, it is appreciated that the ANN non-linear load analyzer **100** could couple to an electric power system at any suitable point, even directly to the customer's non-linear load **116**.

It is appreciated that the ANN non-linear load analyzer **100** determines harmonic contributions from non-linear loads downstream from the connection interface **118**. More particularly, the ANN non-linear load analyzer **100** determines harmonic contributions from non-linear loads downstream from the current transformer **204** (FIG. **2**) which provides the metered current information, described in greater detail hereinbelow. Accordingly, depending upon how the ANN non-linear load analyzer **100** is connected to the service system **102**, loading from one or more customers may be aggregated. For example, in a situation where a customer is billed for harmonic components that the customer injects into the service system **102**, the connection interface **118** may be configured to provide metered voltage and current applicable to that specific customer. In another situation, the ANN non-linear load analyzer **100** might be coupled to a convenient location on service system **102**, such as at a distribution substation, which serves more than one customer.

FIG. **2** is a block diagram illustrating in greater detail an embodiment of the ANN non-linear load analyzer **100** coupled to the simplified single-line diagram of the electric power supply network **104**. The ANN non-linear load analyzer **100** includes an artificial neural network (ANN) **200** and summing circuit **202**.

A metering potential transformer (PT) and a metering current transformer (CT) **204** are illustrated as residing at the connection interface **118**. The PT provides a voltage transformation such that voltage of conductor **106** may be sensed and communicated to voltage transducer **206**. The CT provides a current transformation such that current of connection **106** may be sensed and communicated to current transducer **208**. Other voltage and/or current sensing devices may alternatively meter voltage and current, respectively.

Voltage transducer **206** converts the sensed alternating current (AC) voltage into a signal, such as a digitally sampled signal, that is proportional to the sensed AC voltage from the PT. Sensed voltages may be phase-to-phase voltages or phase-to-neutral voltages. Current transducer **208** converts the sensed AC current into a signal, such as a digitally sampled signal, that is proportional to the sensed AC current from the CT.

Typically, PTs and CTs are available at various points along the electric power system when various other functions associated with operation of the electric power system are performed. For example, a metering PT and a metering CT may be provided for revenue billing. Or, a PT and/or CT may be for protective devices, auxiliary power and/or communication devices. When such PTs and/or CTs **204** are readily available, the associated voltage transducer **206** and/or current transducer **208** may be coupled to those devices. Thus, information corresponding to the voltage and information corresponding to the current may be available from already-available devices for some embodiments of the ANN non-linear load analyzer **100**. In other situations PTs, CTs, voltage transducers **206** and/or the current transducers **208** may not be available. Accordingly, other embodiments of the ANN non-linear load analyzer **100** may be equipped with such devices, or such devices may be separately installed for the ANN non-linear load analyzer **100**.

As illustrated in FIG. **2**, the ANN **200** receives a signal corresponding to metered voltage, via connection **210**. The ANN **200** is configured to output a predicted current $\hat{i}$, via the logical connection **212** (since the predicted current $\hat{i}$ is computationally determined by executing software, the ANN logic **408** illustrated in FIG. **4**, connection **212** is not a physical connection). The predicted current $\hat{i}$ is input into the summing circuit **202** such that the predicted current $\hat{i}$ is summed with the signal corresponding to metered current, provided on connection **214**, such that a difference between the predicted current $\hat{i}$ and the metered current is determined. The output of the summing circuit **202** (the difference between the predicted current $\hat{i}$ and the metered current) is the current error signal, e, output on the logical connection **216**. The current error signal e is returned to the ANN **200**.

As the current error signal e approaches zero, or converges to within a predefined threshold, it is appreciated that the ANN **200** has completed training with respect to predicting current. That is, the ANN **200** is accurately predicting current metered at connection interface **118**, within some predefined threshold.

When predicted current $\hat{i}$ is accurately predicted, the ANN **200** may then computationally determine the harmonic current component, $\hat{i}$—distorted. Information corresponding to the harmonic current component, $\hat{i}$—distorted, is output on connection **218**, and may be used for a variety of purposes, as is well understood in the arts.

FIG. **3** is a conceptual block diagram illustrating an embodiment of the ANN non-linear load analyzer **100**. The ANN **200** (see also FIG. **2**), in this embodiment, includes two artificial neural networks, the training ANN **302** and the estimating ANN **304**. It is appreciated that the training ANN **302**, the estimating ANN **304** and the summing circuit **202** may be implemented as software, firmware, or combinations of software and firmware.

In this conceptual embodiment, the training ANN **302** receives the signal corresponding to metered voltage, via connection **210**. At the end of a training time, or sampling interval, the training ANN **302** outputs the predicted current $\hat{i}$, via connection **212**, to the summing circuit **202**. Metered current is then summed with the predicted current $\hat{i}$ (such that a difference between the predicted current $\hat{i}$ and the metered current is determined). In one embodiment, the metered current at the end of the sampling interval is used for the comparison. (In other embodiments, the metered current used for training may be used when this information is stored for later retrieval.)

The current error signal e is returned on connection **216** to the training ANN **302**. As noted above, when the current error signal e approaches zero, or converges, the training ANN **302** has completed training with respect to predicting current. In some embodiments, the current error signal e has converged when the difference between the predicted current $\hat{i}$ and the metered current is less than and/or equal to a predefined threshold.

The metered current may be considered as a pure sinusoidal wave provided by the electric power supply network **104** with harmonic components injected thereon by the customer non-linear load **116** (FIGS. **1** and **2**). Thus, the corresponding predicted current $\hat{i}$ is a computed sinusoidal wave current distorted by the harmonics. The computed predicted current $\hat{i}$ may be represented by any suitable mathematical equation or algorithm, which is selected based upon the design of the particular embodiment of the ANN non-linear load analyzer **100**.

In one embodiment, the load admittance is calculated. Accordingly, the load admittance is modeled by a suitable equation with determined weights. In another embodiment, weights associated with the equation defining the predicted current $\hat{i}$ are determined. After the weights have been determined by the training ANN **302**, the weights are communicated to the estimating ANN **304** (represented conceptually by the directional arrow **306**).

While the estimating ANN **304** determines the harmonic current component ($\hat{i}$—distorted), the training ANN **302** in one embodiment continues sampling. Weights are adjusted at each sample depending on the degree of convergence (the difference between the predicted current $\hat{i}$ and the metered current). When the estimating ANN **304** has determined the harmonic current component ($\hat{i}$—distorted), the estimating ANN **304** receives another set of weights from the training ANN **302**. In one embodiment, the received second set of weights are the most current value of the weights determined by the training ANN **302**. Then, the estimating ANN **304** determines another harmonic current component based upon the new weights. The above-described process may be continuously repeated.

Depending upon the embodiment, the training ANN **304** may then restart the training process to predict another predicted current î. Thus, after some period of time, weights associated with the subsequent predicted current î are determined. The newly determined weights may or may not equal the previously determined weights, depending upon whether the nature of the customer's non-linear load **116** and/or the power supply have changed by the time the second training period has been completed. That is, if the degree of convergence has changed since the previous sampling period, newly computed weights will be different. For example, a customer may have turned on (or off) a solid-state load, thereby changing the nature of the customer's non-linear load **116**, thereby resulting in a change in the degree of convergence. Accordingly, the training and determining harmonic components may be performed on a continual basis.

The estimating ANN **304** receives the determined weights (for the load admittance and/or predicted current î equation). The estimating ANN **304** then computationally applies the weights to a pure sinusoidal wave **308**. Distortion in the output of the sinusoidal wave (distorted by the determined weights) is then used to determine the harmonic current component (î—distorted) associated with the customer non-linear load **116**.

Information corresponding to the harmonic current component (î—distorted) and/or a determined load admittance associated with the customer non-linear load **116** may then be communicated onto connection **218**, and may be used for a variety of purposes, as is well understood in the arts.

FIG. **4** is a block diagram illustrating in greater detail an exemplary embodiment of an ANN non-linear load analyzer **100**. The exemplary embodiment comprises a processing system **402** and summing circuit **202**. Processing system **402** includes a processor **404** and memory **406**. In one embodiment, memory **406** includes regions for storing the summing circuit **202** (implemented as logic), artificial neural network (ANN) logic **408**, the above-described weights **410** and admittance **412**, data corresponding to the current error signal e **414**, the predicted current î **416**, and/or the harmonic current component (î—distorted) **418**, depending upon the particular embodiment. The information is saved into memory **406** for ongoing processing, and/or may be saved for later processing and/or analysis. In other embodiments, the information may be saved in other memories as needed, such as buffers or random access memories.

Also included are suitable interfaces that provide coupling to the above-described connections which communicate the various information. The metered voltage interface **420** provides coupling to connection **210** such that information corresponding to the metered voltage is received. The metered current interface **422** provides coupling to connection **214** such that information corresponding to the metered current is received. The output device interface **424** provides coupling to connection **218** such that information corresponding to the harmonic current component (î—distorted) is transmitted to a suitable device.

The above described components are communicatively coupled to each other via bus **426** and connections **428**. In alternative embodiments of processing system **402**, the above-described components are connectivley coupled to processor **404** in a different manner than illustrated in FIG. **4**. For example, one or more of the above-described components may be directly coupled to processor **404** or may be coupled to processor **404** via intermediary components (not shown).

The above-described interfaces **420**, **422** and/or **424** may be passive devices, or they may be active devices that process the received/transmitted signals into a suitable format. For example, the metered voltage interface **420** may be a simple coupling to connection **210** when the voltage transducer **206** (FIG. **2**) provides a suitable metered voltage signal that may be directly communicated onto bus **428** such that information corresponding to metered voltage is received by processor **404**. In another embodiment, the metered voltage interface **420** processes the metered voltage information received on connection **210** into a suitable signal that is directly communicated onto bus **428**. As another example, the output device interface **426** may communicate information corresponding to the harmonic current component (î—distorted) to a display such that a voltage or current signal is displayed to a viewer. Or, output device interface **426** may communicate information corresponding to the harmonic current component (î—distorted) to another processing system or memory for future analysis.

In various embodiments, the summing circuit **202** could be implemented as software (with its own processor and memory, not shown), as firmware, or as a combination of firmware and software. In another embodiment, an interface (not shown) to receive the metered current information on connection **214** is included such that the processor **404** computationally determines the current error signal e. In this embodiment, the interfaces **422** and **424** are omitted.

FIG. **5** shows a flow chart **500** illustrating a process used by an embodiment of ANN non-linear load analyzer **100** (FIGS. **1-4**). The flow chart **500** of FIG. **5** shows the architecture, functionality, and operation of an embodiment for implementing the ANN logic **408** (FIG. **4**). An alternative embodiment implements the logic of flow chart **500** with hardware configured as a state machine. In this regard, each block may represent a module, segment or portion of code, which comprises one or more executable instructions for implementing the specified logical function(s). It should also be noted that in alternative embodiments, the functions noted in the blocks may occur out of the order noted in FIG. **5**, or may include additional functions. For example, two blocks shown in succession in FIG. **5** may in fact be substantially executed concurrently, the blocks may sometimes be executed in the reverse order, or some of the blocks may not be executed in all instances, depending upon the functionality involved, as will be further clarified hereinbelow. All such modifications and variations are intended to be included herein within the scope of this disclosure.

The process begins at block **502**. At block **504**, voltage on an electric power system is metered. At block **506**, current on the electric power system is metered. At block **508**, a predicted current based upon the metered voltage is determined. At block **510**, the predicted current is compared with the metered current. At block **512**, a harmonic current component is determined using at least one weight determined when the predicted current converges with the metered current. The process ends at block **514**.

An alternative embodiment of the ANN non-linear load analyzer **100** may be configured as an ANN source model identifier **600**. FIG. **6** is a block diagram illustrating an embodiment of the ANN source model identifier **600** coupled to a simplified portion of an electric power supply service system **602**. Service system **602** is ultimately coupled to a source equivalent circuit **604**. Source equivalent circuit **604** may comprise an electric power supply network together with multiple loads (which could be linear or non-linear). Service system **602** may represent either a single-phase or a three-phase system. Furthermore, the operating voltage of service system **602** may range from customer service voltage, to a distribution voltage, up through EHV. Also, service system **602** may be radial or part of a network.

Typically, service is provided from an electric power supply network, as part of the source equivalent circuit **604**, through a conductor **606** to a non-linear load **616**. Often, service is provided to multiple customers over a common component, illustrated here as conductor **606**. A non-linear load **616** may tap off from the conductor **606** at the connection interface **618**. Here, conductor **620** is illustrated as providing service from the connection interface **618** to non-linear load **616**.

It is appreciated that the above-described service system **602** is a very simplified diagram of an exemplary service system. Other service systems may provide service using transformers (not shown), or provide service directly from a substation bus bar (not shown). Service voltages may vary from one service system to another, or may be of the same voltage. Also, voltages along a service system may vary if transformers are employed to alter voltages. As noted previously, service system **602** may represent either a single-phase and/or a three-phase system. As a non-limiting example, conductor **606** could be a three-phase conductor network and the service provided to the non-linear load **616** could be single-phase.

Many service variations are possible which may be analyzed for harmonics by embodiments of the ANN source model identifier **600**. Accordingly, the ANN source model identifier **600** may be configured to couple to single-phase, two-phase and/or three-phase systems; may be configured to couple to various system voltages; and may even be configured to couple to power supply systems of different operating frequencies (such as, but not limited to, the 60 hertz system commonly employed in the United States, or the 50 hertz system commonly employed in European systems).

Embodiments of the ANN source model identifier **600** are configured to conveniently couple to a service system **602**, and/or the non-linear load **616**, such that data may be collected to determine harmonic components caused by the non-linear load **616**. In FIG. **6**, a simplified connector **622** illustrates the ANN source model identifier **600** coupled to the connection interface **618** that provides service to the non-linear load **616** in this simplified example. Greater detail of the various connection aspects of the ANN source model identifier **600** are provided below. However, it is appreciated that the ANN source model identifier **600** could couple to an electric power system at any suitable point.

It is appreciated that the ANN source model identifier **600** determines harmonic contributions from non-linear loads downstream from the connection interface **618**. More particularly, the ANN source model identifier **600** determines harmonic contributions from non-linear loads downstream from the potential transformer and current transformer **704** (FIG. **7**) which provides the metered voltage information, described in greater detail hereinbelow. Accordingly, depending upon how the ANN source model identifier **600** is connected to the service system **602**, loading from one or more customers may be aggregated. For example, in a situation where a customer is billed for harmonic components that the customer injects into the service system **602**, the connection interface **618** may be configured to provide metered voltage and current applicable to that specific customer. In another situation, the ANN source model identifier **600** might be coupled to a convenient location on service system **602**, such as at a distribution substation, which serves more than one customer.

FIG. **7** is a block diagram illustrating in greater detail an embodiment of the ANN source model identifier **600** coupled to the simplified single-line diagram of the source equivalent circuit **604**. The ANN source model identifier **600** includes an artificial neural network (ANN) **700** and summing circuit **702**.



A metering potential transformer (PT) and metering current transformer (CT) **704** are illustrated as residing at the connection interface **618**. The PT provides a voltage transformation such that voltage of conductor **606** may be sensed and communicated to voltage transducer **708**. The CT provides a current transformation such that current of conductor **606** may be sensed and communicated to current transducer **706**. Other voltage and/or current sensing devices may alternatively meter voltage and current, respectively.

Voltage transducer **708** converts the sensed alternating current (AC) voltage into a signal, such as a digitally sampled signal, that is proportional to the sensed AC voltage from the PT. Sensed voltages may be phase-to-phase voltages or phase-to-neutral voltages. Current transducer **706** converts the sensed AC current into a signal, such as a digitally sampled signal, that is proportional to the sensed AC current from the CT.

As noted previously, PTs and CTs are typically available at various points along an electric power system when various other functions associated with operation of the electric power system are performed. Thus, information corresponding to the voltage and information corresponding to the current may be available from already-available devices for some embodiments of the ANN source model identifier **600**. In other situations PTs, CTs, voltage transducers **708** and/or current transducers **706** may not be available. Accordingly, other embodiments of the ANN source model identifier **600** may be equipped with such devices, or such devices may be separately installed for the ANN source model identifier **600**.

As illustrated in FIG. **7**, the ANN **700** receives a signal corresponding to metered current, via connection **710**. The ANN **700** is configured to output a predicted voltage $\hat{v}$, via the logical connection **712** (since the predicted voltage $\hat{v}$ is computationally determined by executing software, the ANN logic **908** illustrated in FIG. **9**, connection **712** is not a physical connection). The predicted voltage $\hat{v}$ is input into the summing circuit **702** such that the predicted voltage $\hat{v}$ is summed with the signal corresponding to metered voltage, provided on connection **714**, such that a difference between the predicted voltage $\hat{v}$, and the metered voltage is determined. The output of the summing circuit **702** (the difference between the predicted voltage $\hat{v}$ and the metered voltage) is the voltage error signal, e, output on the logical connection **716**. The voltage error signal e is returned to the ANN **700**.

As the voltage error signal e approaches zero, or converges to within a predefined threshold, it is appreciated that the ANN **700** has completed training with respect to predicting voltage. That is, the ANN **700** is accurately predicting voltage metered at connection interface **618**, within some predefined threshold.

When predicted voltage $\hat{v}$ is accurately predicted, the ANN **700** may then computationally determine the harmonic voltage component, $\hat{v}$—distorted. Information corresponding to the harmonic voltage component, $\hat{v}$—distorted, is output on connection **718**, and may be used for a variety of purposes, as is well understood in the arts.

FIG. **8** is a conceptual block diagram illustrating an embodiment of the ANN source model identifier **600**. The ANN **700** (see also FIG. **7**), in this embodiment, includes two artificial neural networks, the training ANN **802** and the estimating ANN **804**. It is appreciated that the training ANN **802**, the estimating ANN **804** and the summing circuit **802** may be implemented as software, firmware, or combinations of software and firmware.

In this conceptual embodiment, the training ANN **802** receives the signal corresponding to metered current, via connection **710**. At the end of a training time, or sampling interval, the training ANN **802** outputs the predicted voltage $\hat{v}$, via connection **712**, to the summing circuit **702**. Metered voltage is then summed with the predicted voltage $\hat{v}$ (such that a difference between the predicted voltage $\hat{v}$ and the metered voltage is determined). In one embodiment, the voltage at the end of the sampling interval is used for the comparison. (In other embodiments, the metered voltage used for training may be used when this information is stored for later retrieval.)

The voltage error signal e is returned on connection **716** to the training ANN **802**. As noted above, when the voltage error signal e approaches zero, or converges, the training ANN **802** has completed training with respect to predicting voltage. In some embodiments, the voltage error signal e has converged when the difference between the predicted voltage $\hat{v}$ and the metered voltage is less than and/or equal to a predefined threshold.

The metered voltage may be considered as a pure sinusoidal wave provided by the source equivalent circuit **604** with harmonic components injected thereon by the non-linear load **616** (FIGS. **6** and **7**). Thus, the corresponding predicted voltage $\hat{v}$ is a computed sinusoidal wave voltage distorted by the harmonics. The computed predicted voltage $\hat{v}$ may be represented by any suitable mathematical equation or algorithm, which is selected based upon the design of the particular embodiment of the ANN source model identifier **600**.

In one embodiment, the source equivalent circuit **604** impedance is modeled. Accordingly, the impedance of the source equivalent circuit **604** is modeled by a suitable equation with determined weights. In another embodiment, weights associated with the equation defining the predicted voltage $\hat{v}$ are determined. After the weights have been determined by the training ANN **802**, the weights are communicated to the estimating ANN **804** (represented conceptually by the directional arrow **806**).

While the estimating ANN **804** determines the harmonic voltage component ($\hat{v}$—distorted), the training ANN **802** in one embodiment continues sampling. Weights are adjusted at each sample depending on the degree of convergence (the difference between the predicted voltage $\hat{v}$ and the metered voltage). When the estimating ANN **804** has determined the harmonic voltage component ($\hat{v}$—distorted), the estimating ANN **804** receives another set of weights from the training ANN **802**. In one embodiment, the received second set of weights are the most current value of the weights determined by the training ANN **802**. Then, the estimating ANN **804** determines another harmonic voltage component based upon the new weights. The above-described process may be continuously repeated.

Depending upon the embodiment, the training ANN **804** may then restart the training process to predict another predicted voltage $\hat{v}$. Thus, after some period of time, weights associated with the subsequent predicted voltage $\hat{v}$ are determined. The newly determined weights may or may not equal the previously determined weights, depending upon whether the nature of the non-linear load **616** and/or the power supply have changed by the time the second training period has been completed. That is, if the degree of convergence has changed since the previous sampling period, newly computed weights will be different. For example, a customer may have turned on (or off) a solid-state load, thereby changing the nature of the non-linear load **616**, thereby resulting in a change in the degree of convergence. Accordingly, the training and determining harmonic components may be performed on a continual basis.

The estimating ANN **804** receives the determined weights (for the source equivalent circuit **604** impedance and/or predicted voltage $\hat{v}$ equation). The estimating ANN **804** then computationally applies the weights to a pure sinusoidal wave **808**. Distortion in the output of the sinusoidal wave (distorted by the determined weights) is then used to determine the harmonic voltage component ($\hat{v}$—distorted) associated with the source equivalent circuit **604**.

Information corresponding to the harmonic voltage component ($\hat{v}$—distorted) and/or a determined impedance associated with the source equivalent circuit **604** may then be communicated through connection interface **718**, and may be used for a variety of purposes, as is well understood in the arts.

FIG. **9** is a block diagram illustrating in greater detail an exemplary embodiment of an ANN source model identifier **600**. The exemplary embodiment comprises a processing system **902** and summing circuit **702**. Processing system **902** includes a processor **904** and memory **906**. In one embodiment, memory **906** includes regions for storing the summing circuit **702** (implemented as logic), artificial neural network (ANN) logic **908**, the above-described weights **910** and admittance **912**, data corresponding to the voltage error signal e **914**, the predicted voltage $\hat{v}$ **916**, and/or the harmonic voltage component ($\hat{v}$—distorted) **918**, depending upon the particular embodiment. The information is saved into memory **906** for ongoing processing, and/or may be saved for later processing and/or analysis. In other embodiments, the information may be saved in other memories as needed, such as buffers or random access memories.

Also included are suitable interfaces that provide coupling to the above-described connections which communicate the various information. The metered current interface **920** provides coupling to connection **710** such that information corresponding to the metered current is received. The metered voltage interface **922** provides coupling to connection **714** such that information corresponding to the metered voltage is received. The output device interface **924** provides coupling to connection **718** such that information corresponding to the harmonic voltage component ($\hat{v}$—distorted) is transmitted to a suitable device.

The above described components are communicatively coupled to each other via bus **926** and connections **928**. In alternative embodiments of processing system **902**, the above-described components are connectively coupled to processor **904** in a different manner than illustrated in FIG. **9**. For example, one or more of the above-described components may be directly coupled to processor **904** or may be coupled to processor **904** via intermediary components (not shown).

The above-described interfaces **920**, **922** and/or **924** may be passive devices, or they may be active devices that process the received/transmitted signals into a suitable format. For example, the metered current interface **920** may be a simple coupling to connection **710** when the current transducer **706** (FIG. **7**) provides a suitable metered current signal that may be directly communicated onto bus **928** such that information corresponding to metered current is received by processor **904**. In another embodiment, the metered current interface **920** processes the metered current information received on connection **710** into a suitable signal that is directly communicated onto bus **928**. As another example, the output device interface **926** may communicate information corresponding to the harmonic voltage component ($\hat{v}$—distorted) to a display such that a voltage or current signal is displayed to a viewer. Or, output device interface **926** may communicate information corresponding to the harmonic voltage component ($\hat{v}$—distorted) to another processing system or memory for future analysis.

In various embodiments, the summing circuit **702** could be implemented as software (with its own processor and memory, not shown), as firmware, or as a combination of firmware and software. In another embodiment, an interface (not shown) to receive the metered voltage information on connection **714** is included such that the processor **904** computationally determines the voltage error signal e. In this embodiment, the interfaces **922** and **924** are omitted.

FIG. **10** shows a flow chart **1000** illustrating a process used by an embodiment of ANN source model identifier **600** (FIG. **6**-FIG. **9**). The flow chart **1000** of FIG. **10** shows the architecture, functionality and operation of an embodiment for implementing the ANN logic **908** (FIG. **9**). An alternative embodiment implements the logic of flow chart **1000** with hardware configured as a state machine. In this regard, each block may represent a module, segment or portion of code, which comprises one or more executable instructions for implementing the specified logical function(s). It should also be noted that in alternative embodiments, the functions noted in the blocks may occur out of the order noted in FIG. **10**, or may include additional functions. For example, two blocks shown in succession in FIG. **10** may in fact be substantially executed concurrently, the blocks may sometimes be executed in the reverse order, or some of the blocks may not be executed in all instances, depending upon the functionality involved, as will be further clarified hereinbelow. All such modifications and variations are intended to be included herein within the scope of this disclosure.

The process begins at block **1002**. At block **1004**, voltage on a source equivalent circuit is metered. At block **1006**, current on the source equivalent circuit is metered. At block **1008**, a predicted voltage based upon the metered current is determined. At block **1010**, the predicted voltage is compared with the metered voltage. At block **1012**, a harmonic voltage component is determined using at least one weight determined when the predicted voltage converges with the metered voltage. The process ends at block **1014**.

Embodiments of the ANN logic **408**, and the above-described information, implemented in memory **406** (FIG. **4**) and/or the ANN logic **908**, and the above-described information implemented in memory **906** (FIG. **9**) may be implemented using any suitable computer-readable medium. In the context of this specification, a "computer-readable medium" can be any means that can store or communicate the data associated with, used by or in connection with the instruction execution system, apparatus, and/or device. The computer-readable medium can be, for example, but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, or device now known or later developed.

Processing system **402** and/or processing system **902** are typically a commercially available processor. Examples of commercially available processors include, but are not limited to, a Pentium microprocessor from Intel Corporation, Power PC microprocessor, SPARC processor, PA-RISC processor or 68000 series microprocessor. Many other suitable processors are also available. Or, processing system **402** may be a specially designed and fabricated processor in accordance with embodiments of the ANN non-linear load analyzer **100**. Similarly, processing system **902** could be a specially designed and fabricated processor in accordance with embodiments of the ANN source model identifier **600**.

It should be emphasized that the above-described embodiments are merely examples of the disclosed system and method. Many variations and modifications may be made to the above-described embodiments. All such modifications and variations are intended to be included herein within the scope of this disclosure.

What is claimed is:

**1**. A method for determining harmonics caused by non-linear loads, comprising:
- metering voltage on an electric power system;
- metering current on the electric power system;
- determining a predicted voltage based upon the metered current;
- comparing the predicted voltage with the metered voltage;
- determining a plurality of weights when the predicted voltage converges within a predetermined threshold of the metered voltage;
- determining a harmonic voltage component by computationally combining a sinusoidal waveform with the plurality of weights; and
- communicating the determined weights to an estimating artificial neural network when the predicted voltage converges with the metered voltage.

**2**. The method of claim **1**, further comprising determining when the predicted voltage converges with the metered voltage by comparing the predicted voltage with the metered voltage.

**3**. The method of claim **1**, further comprising:
- metering single-phase voltage; and
- metering single-phase current.

**4**. The method of claim **1**, further comprising:
- metering three-phase voltage; and
- metering three-phase current.

**5**. The method of claim **1**, further comprising:
- again determining predicted voltage based upon the metered current;
- again comparing the predicted voltage with metered voltage;
- determining another plurality of weights; and
- determining a second harmonic voltage component using the other plurality of weights.

**6**. A system that determines harmonics caused by non-linear loads, comprising:
- an artificial neural network configured to receive information corresponding to metered current, to train itself such that a predicted voltage determined from the information corresponding to metered current converges with a metered voltage, and to determine a harmonic voltage component using a plurality of weights determined when the predicted voltage converges with the metered voltage wherein a sinusoidal wave is computationally combined with the plurality of determined weights to determine the harmonic voltage component; a summing circuit that compares the determined predicted voltage and the metered voltage, and that outputs a voltage error to the artificial neural network such that when the voltage error is less than a predefined threshold, the artificial neural network determines the predicted voltage converges with the metered voltage; and
- a processor configured to execute the artificial neural network.

**7**. The system of claim **6**, wherein the determined predicted voltage converges with the metered voltage within a predefined threshold.

**8**. The system of claim **6**, further comprising a memory wherein the artificial neural network resides.

9. The system of claim 6, wherein the voltage error corresponds to a difference between the metered voltage and the predicted voltage.

10. The system of claim 6, further comprising a voltage transducer that receives a signal corresponding to voltage from a potential transformer, and that outputs a second signal corresponding to the metered voltage, the second signal communicated to the summing circuit as the metered voltage.

11. The system of claim 6, further comprising a current transducer that receives a signal corresponding to current from a current transformer, and that outputs a second signal corresponding to the metered current, the second signal communicated to the artificial neural network as the metered current.

12. The system of claim 6, wherein the artificial neural network further comprises:

a training artificial neural network that determines the predicted voltage from the information corresponding to metered current and that determines the plurality of weights determined when the predicted voltage converges with the metered voltage; and

a separate estimating artificial neural network that determines the harmonic voltage component using the plurality of determined weights received from the training artificial neural network.

13. A system for determining harmonics caused by non-linear loads, comprising:

means for receiving metered voltage from an electric power system;

means for receiving metered current from the electric power system;

means for determining a predicted voltage based upon the metered current;

means for comparing the predicted voltage with the metered voltage;

means for determining when the predicted voltage converges with the metered voltage by comparing the predicted voltage with the metered voltage; means for determining a plurality of weights when the predicted voltage converges with the metered voltage; and

means for determining a harmonic voltage component using the plurality of determined weights, where a sinusoidal wave is computationally combined with the plurality of determined weights to determine the harmonic component.

14. The system of claim 13, wherein the means for determining when the predicted voltage converges with the metered voltage comprises means for comparing a difference between the predicted voltage and the metered voltage to a predefined threshold.

15. The system of claim 13, further comprising:

means for metering single-phase voltage; and

means for metering single-phase current.

16. The system of claim 13, further comprising:

means for metering three-phase voltage; and

means for metering three-phase current.

17. A computer-readable medium embodying a program executable by a processor circuit for determining harmonics caused by non-linear loads, the program comprising:

logic configured to receive information corresponding to a metered current from an electric power system;

logic configured to receive information corresponding to a metered voltage on the electric power system;

logic configured to determine a predicted voltage based upon the metered current;

logic configured to determine when the predicted voltage converges with the metered voltage by comparing the predicted voltage with the metered voltage; logic configured to determine a plurality of weights when the predicted voltage converges with the metered voltage; and

logic configured to determine a harmonic voltage component using the plurality of determined weights, where a sinusoidal wave is computationally combined with the plurality of determined weights to determine the harmonic component.

18. The computer-readable medium of claim 17, further comprising logic configured to compare a difference between the predicted voltage and the metered voltage to a predefined threshold.

19. An artificial neural network that determines harmonics caused by non-linear loads, comprising:

a training artificial neural network that determines a predicted voltage from a metered current, and that determines a plurality of weights when the predicted voltage converges with a metered voltage when a voltage error is less than a predefined threshold; a comparison circuit that compares the determined predicted voltage and the metered voltage and outputs the voltage error to the training artificial neural network; and

a separate estimating artificial neural network that determines a harmonic voltage component using the determined weights received from the training artificial neural network.

20. The artificial neural network of claim 19, wherein the training artificial neural network trains itself such that the predicted voltage is determined which converges with the metered voltage.

21. The artificial neural network of claim 20, wherein the training artificial neural network compares the predicted voltage with the metered voltage to determine when the predicted voltage converges with the metered voltage.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

# CERTIFICATE OF CORRECTION

PATENT NO. : 7,720,620 B2
APPLICATION NO. : 11/337630
DATED : May 18, 2010
INVENTOR(S) : Ronald G. Harley et al.



It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

At column 1, line 9, delete “continuation-in-pad” and replace with --continuation-in-part--.

At column 7, line 63, delete “above-described components are connectivley coupled to” and replace with --above-described components are connectively coupled to--.

At column 8, lines 7 and 12, delete “bus 428” and replace with --bus 426--.

At column 8, lines 13 and 16, delete “interface 426” and replace with --interface 424--.

At column 11, line 1, delete “summing circuit 802” and replace with --summing circuit 702--.

At column 12, lines 59 and 64, delete “bus 928” and replace with --bus 926--.

At column 12, line 65 and column 13, line 1, delete “interface 926” and replace with --interface 924--.

Signed and Sealed this

Thirteenth Day of July, 2010

David J. Kappos

David J. Kappos
*Director of the United States Patent and Trademark Office*